

The bright unidentified γ -ray source 1FGL J1227.9–4852: can it be associated with a low-mass X-ray binary?

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ABSTRACT

We present an analysis of high energy (HE; 0.1–300 GeV) γ -ray observations of 1FGL J1227.9–4852 with the *Fermi* Gamma-ray Space Telescope, follow-up radio observations with the Australia Telescope Compact Array, Giant Metrewave Radio Telescope and Parkes radio telescopes of the same field and follow-up optical observations with the ESO VLT. We also examine archival *XMM-Newton* and *INTEGRAL* X-ray observations of the region around this source. The γ -ray spectrum of 1FGL J1227.9–4852 is best fitted with an exponentially cut-off power law, reminiscent of the population of pulsars observed by *Fermi*. A previously unknown, compact radio source within the 99.7 per cent error circle of 1FGL J1227.9–4852 is discovered and has a morphology consistent either with an AGN core/jet structure or with two roughly symmetric lobes of a distant radio galaxy. A single bright X-ray source XSS J12270–4859, a low-mass X-ray binary, also lies within the 1FGL J1227.9–4852 error circle and we report the first detection of radio emission from this source. The potential association of 1FGL J1227.9–4852 with each of these counterparts is discussed. Based upon the available data we find the association of the γ -ray source to the compact double radio source unlikely and suggest that XSS J12270–4859 is a more likely counterpart to the new HE source. We propose that XSS J12270–4859 may be a millisecond binary pulsar and draw comparisons with PSR J1023+0038.

Key words: pulsars: general – galaxies: active – gamma-rays: general – radio continuum: galaxies – X-rays: individual: XSS J12270–4859.

1 INTRODUCTION

The first year (1FGL) catalogue of the *Fermi* Large Area Telescope (LAT, Abdo et al. 2010c) lists in excess of 1400 γ -ray sources (0.1–300 GeV) across the entire sky of which more than 600 are not associated with a known γ -ray emitting object or source class and are hence considered unidentified. In an attempt to identify interesting sources for follow-up, we cross-correlated the 1FGL catalogue with

the latest hard X-ray catalogues from *Swift* and *INTEGRAL* (Bird et al. 2010; Cusumano et al. 2010). The cross-correlation yields 50–60 sources which are good candidates for having hard X-ray counterparts. The vast majority of these are blazars (see Abdo et al. 2010a) or bright well-known high-energy (HE) Galactic sources such as the Crab pulsar; this is in agreement with the early findings of Ubertini et al. (2009) who correlated the 3-month *Fermi* Bright Source List with hard X-ray catalogues.

One unidentified *Fermi* source associated through the cross-correlation, 1FGL J1227.9–4852, does not fall into these ‘common’ source classes; it correlates with the hard X-ray source XSS

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J12270–4859 (Bird et al. 2010; Cusumano et al. 2010), an unusual low-mass X-ray binary¹ (LMXB) (Saitou et al. 2009; de Martino et al. 2010). The 1FGL source location is approximately 14° above the Galactic plane at RA = $12^h 27^m 9$, Dec. = $-48^\circ 52' 7$ (J2000) with a 95 per cent error radius of ~ 6.1 arcmin. The 1FGL catalogue lists it as having no known HE counterpart; however, within the 95 per cent error circle are the previously mentioned hard X-ray and two Two Micron All Sky Survey (2MASS) catalogue objects classified as regular galaxies. There is no known radio source within the error circle, however, there is a single Sydney University Molonglo Sky Survey (SUMSS) source just outside of the 95 per cent radius, SUMSS J122820–485537. de Martino et al. (2010) noted the proximity of SUMSS J122820–485537 to 1FGL J1227.9–4852. However, as shown in Section 2.1 the refined LAT error circle completely discounts this SUMSS source as a potential counterpart.

To date, three high-mass X-ray binaries (HMXBs) have been detected by *Fermi*-LAT: LS I +61° 303 (Abdo et al. 2009b), LS 5039 (Abdo et al. 2009c) and Cyg X-3 (Abdo et al. 2009f). All of these systems contain $>10 M_\odot$ donor stars. The first two sources are seen as persistent, bright variable γ -ray sources, while the latter is a microquasar observed as a HE transient. The location of 1FGL J1227.9–4852 $\sim 14^\circ$ off the Galactic plane rules out the possibility of it being a distant HMXB due to the absence of massive stars at high Galactic latitudes.

XSS J12270–4859 makes for an intriguing potential counterpart and, if associated with the γ -ray source, would be the first LMXB detected by *Fermi*. This X-ray source was recently the subject of a detailed study by de Martino et al. (2010) who performed an analysis of targeted *XMM-Newton* and optical *V*-band observations combined with archival *INTEGRAL* and *RXTE* observations; they also noted its spatial coincidence with a 1FGL catalogue source. While there are a number of X-ray sources in the field, XSS J12270–4859 is far and away the brightest and is characterized by de Martino et al. (2010) as a persistent X-ray source which exhibits flaring and dipping on time-scales of tens of minutes, as originally reported by Saitou et al. (2009) from *Suzaku* observations. The spectrum is reported to be best represented by an absorbed power law with a hydrogen column density of $\sim 10^{21} \text{ cm}^{-2}$. No evidence of a cut-off in the spectrum is found up to 55 keV. The unabsorbed 0.2–100 keV flux is given as $(4.2 \pm 0.2) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ giving a luminosity of $\sim 5.0 \times 10^{33} \text{ erg s}^{-1}$ if the source is 1 kpc distant. de Martino et al. (2010) also report optical *V*-band observations made with the Rapid Eye Mount (REM) robotic telescope at the ESO, La Silla observatory. They find a periodic signal which yields a period of $4.32 \pm 0.01 \text{ h}$ when fitted with a sinusoid. They note that the weak quasi-sinusoidal variability observed in the *XMM-Newton* quiescent X-ray light curve is consistent with the 4.32-h period and could be ascribed to a binary orbit. They conclude that the source is likely a peculiar, low-luminosity LMXB with a possible orbital period of 4.32 h. XSS J12270–4859 has also been reported as a hard X-ray source detected at energies up to 100 keV by *INTEGRAL* (Bird et al. 2010) and *Suzaku* (Saitou et al. 2009).

We present here a detailed analysis of the *Fermi* HE γ -ray data and additional follow-up radio observations of the region. Together with archival X-ray and hard X-ray data we attempt to explain the underlying nature of this mysterious source.

¹ XSS J12270–4859 was originally classified as an intermediate polar cataclysmic variable (Butters et al. 2008). However, recent independent studies have cast doubt on this classification (see Saitou et al. 2009; de Martino et al. 2010).

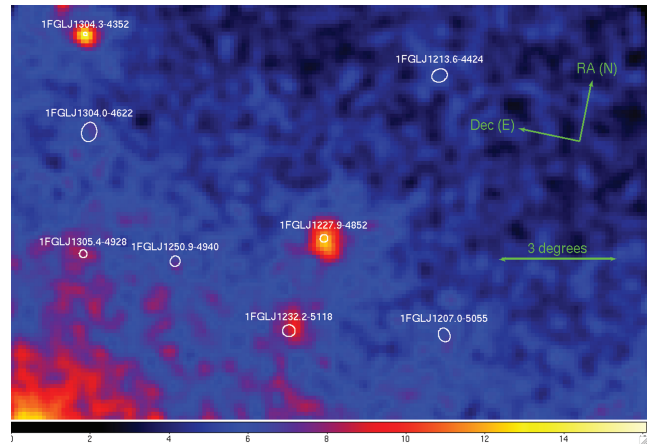


Figure 1. The smoothed counts map for 100 MeV–300 GeV of the region around 1FGL J1227.9–4852 using the ~ 25.5 -month data set described in the text; the white ellipses denote the 95 per cent error circles of the 1FGL sources within the field (Abdo et al. 2010c). An 0.3° Gaussian smoothing function was applied to the 0.1° bins.

2 OBSERVATIONS AND DATA REDUCTION

2.1 *Fermi*-LAT observations of 1FGL J1227.9–4852

The LAT is the primary instrument onboard *Fermi*; it is an electron–positron pair production telescope, featuring solid state silicon trackers and cesium iodide calorimeters, sensitive to photons from $\sim 20 \text{ MeV}$ to $>300 \text{ GeV}$ (Atwood et al. 2009). The observatory operates principally in survey mode; the telescope is rocked north and south on alternate orbits to provide more uniform coverage so that every part of the sky is observed for $\sim 30 \text{ min}$ every 3 h.

The LAT analysis data set spanned 2008-08-04 UTC 15:43:37 to 2010-09-15 UTC 04:46:08. The data were reduced and analysed using the *Fermi* Science Tools v9r15 package.² The standard onboard filtering, event reconstruction, and classification were applied to the data (Atwood et al. 2009), and for this analysis the high-quality (‘diffuse’) photon event class is used. Throughout the analysis, the ‘Pass 6 v3 Diffuse’ (P6_V3_DIFFUSE) instrument response functions (IRFs) are applied. Time periods when the region around 1FGL J1227.9–4852 was observed at a zenith angle greater than 105° and for observatory rocking angles of greater than 43° before MJD 55077 and greater than 52° after MJD 55077 were also excluded to avoid contamination from the Earth limb photons.

2.1.1 Imaging and timing analysis

The photon count map of the region surrounding 1FGL J1227.9–4852 is shown in Fig. 1. The source can be seen to be bright and isolated. The source is localized using the point-fit likelihood tool (see Abdo et al. 2010c). For this and subsequent likelihood analyses a spectral-spatial model containing point and diffuse sources was created and the parameters obtained from a simultaneous maximum likelihood fit to the data. All point sources within a 15° region around 1FGL J1227.9–4852 were included in the model (36 sources listed in the 1FGL catalogue) as were the Galactic and isotropic diffuse contributions. The point sources were modelled by a simple power-law function and the spectral parameters

² See the FSSC website for details of the Science Tools: <http://fermi.gsfc.nasa.gov/ssc/data/analysis/>

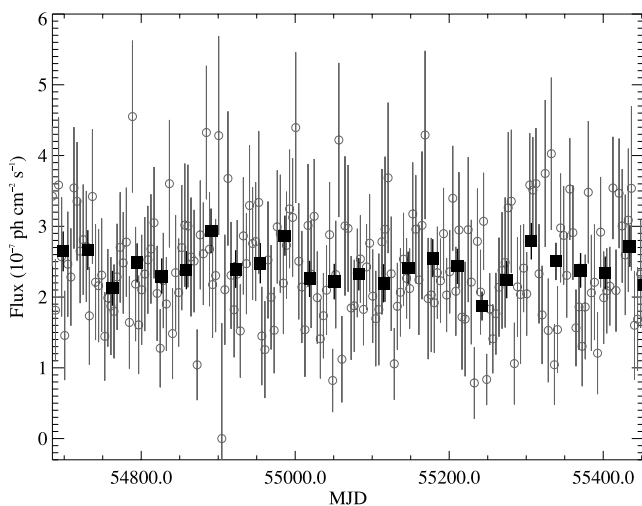


Figure 2. The *Fermi*-LAT 0.1–300 GeV aperture photometry light curve of 1FGL J1227.9–4852 for the first ~ 25.5 months of observations; no background was subtracted and a 1° aperture was used. The grey circles indicate 4-d flux bins; the black squares indicate 32-d flux bins.

were frozen to those reported in the 1FGL catalogue except those sources within 3° of 1FGL J1227.9–4852 for which the spectral parameters were simultaneously fitted. The models used for the Galactic diffuse emission (gll_iem_v02.fit) and isotropic backgrounds (isotropic_iem_v02.txt) were those currently recommended by the LAT team.³ 1FGL J1227.9–4852 is localized at RA = $12^{\text{h}}27^{\text{m}}7$, Dec. = $-48^\circ53'0$ (J2000) with a 95 per cent error radius of 2.9 arcmin; this is compatible with, but much more refined than, the reported position in the 1FGL catalogue (Abdo et al. 2010c). A LAT aperture photometry light curve was extracted for the source using the gtbins tool and the exposure correction was then calculated using the gtexposure tool; it should be noted that these tools perform no background subtraction in the light curve generation. A 0.1–300 GeV light curve was produced with 4-d binning and using a 1° aperture. The light curve is shown in Fig. 2 and shows the source to be very stable with no indications of variability on time-scales longer than the 4-d binning; the light curve can be adequately modelled with a constant flux.

A light curve was constructed on a much shorter binning time of 1000 s to search for the 4.32-h periodicity reported by de Martino et al. (2010) in their X-ray observations of XSS J12270–4859. Using the Lomb–Scargle periodogram method (Lomb 1976; Scargle 1982) no significant periodicity was detected at the 4.32-h period or any other period longer than 1000 s. The LAT source 1FGL J1227.9–4852 was one of the ~ 650 sources included in the pulsar search described in Saz Parkinson et al. (2010). Using approximately one year of sky survey mode observations, a search was carried out using diffuse class events above 300 MeV, within a 1.5° radius of the 1FGL Catalogue position. A time-differencing window of 3 d was used and the standard parameter space (up to 64 Hz) was searched, as described in Abdo et al. (2009d) and Saz Parkinson et al. (2010). No significant candidates were found in the search; although these searches would not be sensitive to a millisecond pulsar (MSP).

³ Descriptions of the models are available from the FSSC: <http://fermi.gsfc.nasa.gov/>

2.1.2 Spectral fitting

The *glike* likelihood fitting tool was used to perform the spectral analysis using the model described in Section 2.1.1. 1FGL J1227.9–4852 was initially fitted with a simple power-law model yielding a photon index of $\Gamma \sim 2.49$. This is compatible with the spectral shape reported in the 1FGL catalogue ($\Gamma = 2.45 \pm 0.07$, Abdo et al. 2010c). Subsequent investigation found that the source was best represented by an exponentially cut-off power-law model of the form $E^{-\Gamma} \exp[-(E/E_{\text{cut-off}})]$. The best-fitting spectral parameters are a photon index $\Gamma = 2.21 \pm 0.09$ (stat) $^{+0.35}_{-0.4}$ (syst) with a cut-off at $E_{\text{cut-off}} = 4.1 \pm 1.3$ (stat) $^{+3.3}_{-1.4}$ (syst) GeV and with an integral flux of $[8.8 \pm 0.7$ (stat) $^{+5.1}_{-3.5}$ (syst)] $\times 10^{-8}$ ph cm $^{-2}$ s $^{-1}$ (0.1–300 GeV). This gives a luminosity of $\sim 4.9 (d/1 \text{ kpc})^2 \times 10^{33}$ erg s $^{-1}$ for the source distance d . The maximum likelihood exponential cut-off spectral model has a likelihood test statistic (Mattox et al. 1996) value of ~ 820.8 equating to a formal detection significance of $>27\sigma$. Comparing the results of the maximum likelihood fit of the two spectral models discussed above finds that $-2\Delta \log(\text{Likelihood}) = 15.74$ which implies that the spectral model with the cut-off improves the maximum likelihood at the $\sim 4\sigma$ level over the simple power law. Fig. 3 shows the LAT data; Table 1 presents the fit results of the power-law and exponentially cut-off power-law models.

The possibility of a broken power-law model representing the data was also investigated as this is a common model used to describe

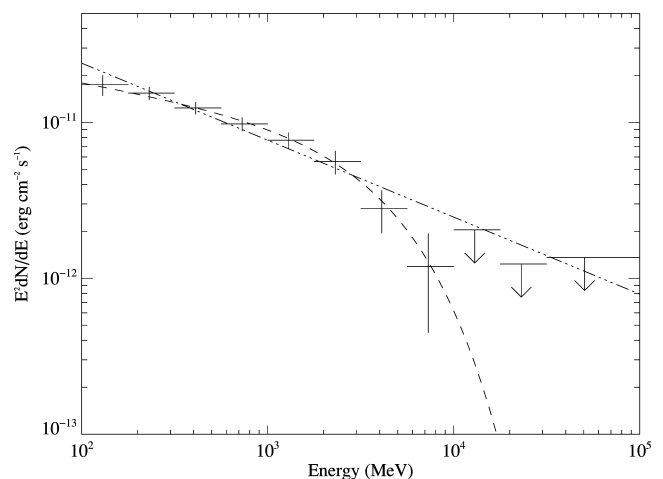


Figure 3. The LAT SED of 1FGL J1227.9–4852. *Fermi* data points are from likelihood fits in each energy bin and are indicated by the black data points; 95 per cent upper limits are calculated for the highest three energy bins indicated by arrows. The dashed line indicates the best-fitting exponential cut-off power law; the dot-dashed line indicates the simple power-law fit, see the text for details.

Table 1. The results of the spectral fits to the 1FGL J1227.9–4852 using the *Fermi*-LAT 0.1–300 GeV data. Only statistical errors are quoted see text for a discussion of systematic error estimates.

Parameter	Power law	Cut-off power law
Photon index	2.49 ± 0.04	2.21 ± 0.09
Cut-off energy (GeV)	–	4.1 ± 1.3
Flux >100 MeV	10.1 ± 0.7	8.8 ± 0.7
10^{-8} ph cm $^{-2}$ s $^{-1}$		

the HE spectra of blazars where a break appears around a few GeV (e.g. Abdo et al. 2009a). However, a reasonable fit was not achieved and no significant increase in TS was achieved using this spectral model.

A number of effects are expected to contribute to the systematic errors quoted above. Primarily, these are uncertainties in the effective area and energy response of the LAT as well as background contamination. The systematics are currently estimated by using outlier IRFs that bracket the nominal ones in effective area. The outlier IRFs are defined by envelopes above and below the P6_V3_DIFFUSE IRFs by linearly connecting differences of (10, 5, 2 per cent) at $\log(E/\text{MeV})$ of (2, 2.75, 4), respectively.

2.2 ATCA and GMRT radio observations

In order to investigate the *Fermi*-LAT source region, we conducted three continuum radio observations with the Australia Telescope Compact Array (ATCA) located in Narrabri, New South Wales, Australia. The ATCA synthesis telescope is an east–west array consisting of six 22-m antennas. The ATCA uses orthogonal polarized feeds and records full Stokes parameters. We carried out the observations with the upgraded Compact Array Broadband Backend (CABB) that provides a new broadband backend system for the ATCA and increases the maximum bandwidth from 128 MHz to 2 GHz.

The observations on 2009 October 02 and November 06 were performed at two frequency bands simultaneously, with central frequencies at 5.5 and 9 GHz. On 2009 October 13, both frequencies were set to 2.45 GHz, using the maximum bandwidth available at the time of 500 MHz. The ATCA was in a very compact configuration on 2009 October 02 (H75) and 2009 October 13 (H168) and in an intermediate configuration (1.5B) on 2009 November 06. The observation log is given in Table 2.

The amplitude and band-pass calibrator was PKS 1934–638, and the antenna’s gain and phase calibration, as well as the polarization leakage, were derived from regular observations of the nearby (~ 3.3 away) calibrator PMN 1215–457. The editing, calibration, Fourier transformation, deconvolution, and image analyses were performed using the MIRIAD software package (Sault, Teuben & Wright 1995; Sault & Killeen 2010). Cleaning was carried out using a combination of multifrequency (Sault & Wieringa 1994) and standard clean algorithms.

Low-frequency observations were performed with the Giant Metrewave Radio telescope (GMRT) near Pune, India. The GMRT consists of 30 fully steerable parabolic dishes of 45-m diameter each spread over distances of up to 25 km. The field was observed on 2010 May 10 at 640 and 240 MHz and on 2010 May 13 at 1400 MHz; see Table 2. The data were converted into FITS format and

Table 2. Log details of the ATCA and GMRT radio observations of 1FGL J1227.9–4852.

Obs. No.	Date	Time on source (h)	Configuration
ATCA			
1	2009 October 02	2.37	H75 @ 5.5 and 9 GHz
2	2009 October 13	1.11	H168 @ 2.45 GHz
3	2009 November 06	7.10	1.5B @ 5.5 and 9 GHz
GMRT			
4	2010 May 10	2.07	240, 640 MHz
5	2010 May 13	2.18	1400 MHz

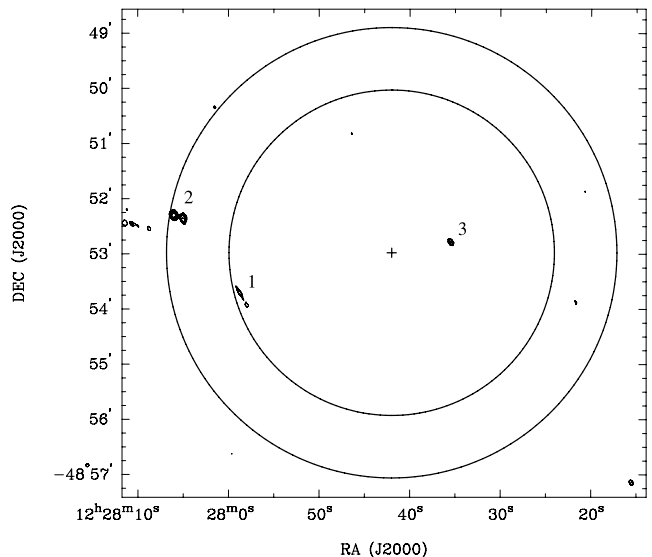


Figure 4. Radio emission at 5.5 GHz at the location of 1FGL J1227.9–4852 from the ATCA observation on 2009 November 06; the circles indicate the 95 and 99.7 per cent *Fermi*-LAT error circles. Contours are at $-3, 3, 5, 10, 20, 30$ and 50 times the level of $0.20 \text{ mJy beam}^{-1}$. The synthesized beam (in the lower right corner) is $5.6 \times 3.5 \text{ arcsec}^2$, with the major axis at a position angle of 28° . Three distinct radio sources are found within the error box.

reduced using standard AIPS procedures. The primary flux calibration was done using 3C286, which was also used as a bandpass calibrator. All observations were phase referenced to PKS 1151–34.

Within the 99.7 per cent error circle of 1FGL J1227.9–4852 three distinct radio sources are detected in the ATCA observations as shown in Fig. 4. All three of these radio sources are new discoveries and are not reported in any current radio catalogues; the subsequently reported source locations are all based upon the data from observation 3.

Source 1: a faint radio source is detected above the 5σ level at a location compatible with the LMXB XSS J12270–4859 (Masetti et al. 2006) and is shown in Fig. 5. The radio source is located at $\text{RA} = 12^{\text{h}}27^{\text{m}}58^{\text{s}}.8$, $\text{Dec.} = -48^\circ53'42''.1$ (J2000) with an error of 0.5 arcsec . The source flux density is $0.18 \pm 0.03 \text{ mJy}$ at 5.5 GHz and $0.14 \pm 0.03 \text{ mJy}$ at 9 GHz with no detection in any of the GMRT bands. It has a spectrum $F_\nu \sim \nu^\alpha$ with $\alpha = -0.5 \pm 0.6$. This implies an optically thin spectrum but could be consistent with a flat spectrum. This is the only radio source within the error circle of 1FGL J1227.9–4852 that has an obvious X-ray counterpart.

Source 2: the brightest radio source in the field, hereafter J122806–485218 (named after the brighter of the two components), is a double source composed of a brighter eastern component, E (possibly a radio core), and a weaker western component, W (most likely a jet or a one-sided lobe), as illustrated in Fig. 6. E is located at $\text{RA} = 12^{\text{h}}28^{\text{m}}06^{\text{s}}.04(\pm 0^{\text{s}}.09)$, $\text{Dec.} = -48^\circ52'18''.05(\pm 0''.10)$ (J2000). The observed flux densities in the 5.5- and 9-GHz bands are $1.36 \pm 0.03 \text{ mJy}$ and $1.03 \pm 0.03 \text{ mJy}$, respectively; E is also detected in the GMRT 1400-MHz band at a flux density of $3.76 \pm 0.06 \text{ mJy}$. This corresponds to a spectral index of $\alpha = -0.72 \pm 0.02$. A few arcseconds away from E lies the western component located at $\text{RA} = 12^{\text{h}}28^{\text{m}}05^{\text{s}}.02(\pm 0^{\text{s}}.15)$, $\text{Dec.} = -48^\circ52'21''.15(\pm 0''.23)$ (J2000). The spectral shape of W is steeper than that of E with a spectral index of $\alpha = -1.09 \pm 0.04$ and with a flux density of $2.42 \pm 0.06 \text{ mJy}$ at 1400 MHz, $0.55 \pm 0.03 \text{ mJy}$ at 5.5 GHz and $0.31 \pm 0.03 \text{ mJy}$ at 9 GHz. In observations 1 and 2 the

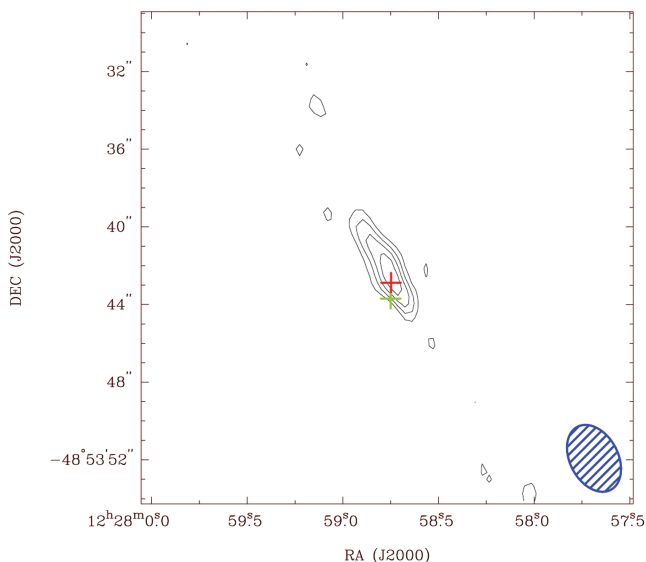


Figure 5. Radio emission at 9 GHz around the location of XSS J12270–4859 from the ATCA observation on 2009 November 06. Contours are at $-3, 3, 4, 5$ and 6 times the rms noise level of $0.20 \text{ mJy beam}^{-1}$. The synthesized beam (in the lower right corner) is $3.7 \times 2.5 \text{ arcsec}^2$, with the major axis at a position angle of 28° . The red cross marks the location of the optical counterpart of Masetti et al. (2006); the green cross marks the *XMM-Newton* X-ray location.

ATCA antennae configurations were in a lower resolution mode and only detected a single component from J122806–485218. During observation 1 the total source flux density was $2.4 \pm 0.2 \text{ mJy}$ at 5.5 GHz and $1.2 \pm 0.1 \text{ mJy}$ at 9 GHz , while during observation 2 the detected flux density was $3.7 \pm 0.6 \text{ mJy}$ at 2.45 GHz . Integrating the component flux densities in observation 3 yields a 5.5-GHz flux density of $2.39 \pm 0.05 \text{ mJy}$ and $1.48 \pm 0.05 \text{ mJy}$ at 9 GHz , which compares favourably with the measurements during observation 1 and gives no significant indication of radio variability. In the GMRT observations at 640 MHz a single source is observed, as the beam size is as big as $24 \times 27 \text{ arcsec}^2$. This is compatible with the location of the two components seen at other frequencies. The flux density at 640 MHz is $33.2 \pm 3.3 \text{ mJy}$, the integral flux density of the two components at 1400 MHz is $6.2 \pm 0.9 \text{ mJy}$, and no source is detected at 240 MHz .

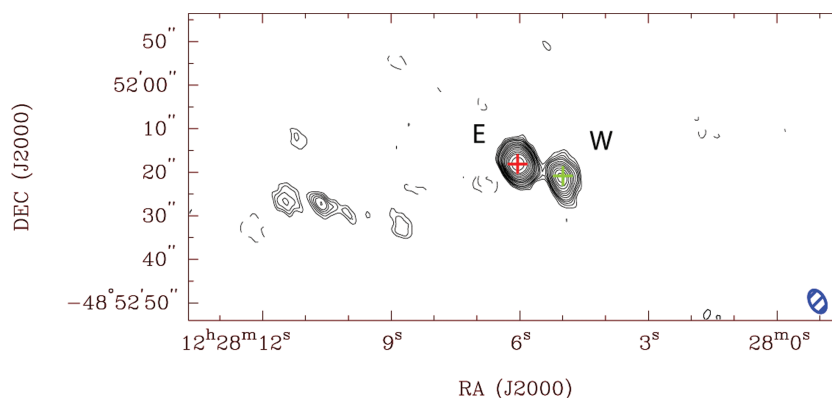


Figure 6. Radio emission at 5.5 GHz around the location of J122806–485218 from the ATCA observation on 2009 November 06. Contours are at $-3, 3, 4, 5, 6, 7, 9, 11, 13, 15, 18, 21, 25, 30, 35, 40$ and 50 times the rms noise level of $0.15 \text{ mJy beam}^{-1}$. The synthesized beam (in the lower right corner) is $5.6 \times 3.5 \text{ arcsec}^2$, with the major axis at a position angle of 28° . The red cross marks the location of the radio core.

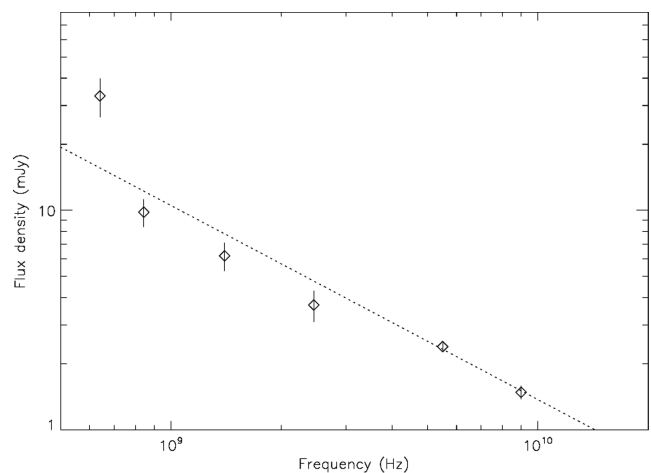


Figure 7. The radio spectrum of the integrated components of the new radio source J122806–485218. The flux densities at 640 MHz and 1400 MHz from GMRT, at 843 MHz from MOST and at $2.45, 5.5$ and 9 GHz from ATCA are all plotted. The vertical bars indicate the 1σ errors on the data points and the dashed line indicates the linear best fit.

The SUMMS survey catalogue is constructed from 843-MHz radio observations made by the Molonglo Observatory Synthesis Telescope (MOST) and does not report a radio source at the location of J122806–485218 (Mauch et al. 2003). A re-analysis of the MOST data indicates a radio source at the location of the western lobe. While it did not satisfy the independent criteria for inclusion into the SUMMS catalogue, in combination with the ATCA data we can confidently report a detection at 843 MHz . The total flux density from the MOST data is $9.8 \pm 1.4 \text{ mJy}$ at 843 MHz . Combining the ATCA, GMRT and MOST data gives a spectral index of $\alpha = -0.88 \pm 0.05$ for the integrated flux density from all components in J122806–485218. This is shown in Fig. 7. The spectral fit matches the radio flux density values well, with the exception of the 640-MHz point which is noticeably higher than would be expected; if the flux density is truly this strong at 640 MHz it implies that either we are resolving the source at 1400 MHz or a very steep component is present.

Source 3: a third source is detected only at 5.5 GHz and only in observation 3. It is located at $\text{RA} = 12^{\text{h}}27^{\text{m}}35^{\text{s}}.5$, $\text{Dec.} = -48^\circ52'47''.2$ (J2000) with an error of 0.3 arcsec . The source is undetected in the 9-GHz observations and has a flux density of $0.23 \pm 0.02 \text{ mJy}$ at

5.5 GHz. Searching the *XMM-Newton* observations of this field yields no significant detection of this source in X-rays.

2.3 Parkes radio observations

The γ -ray characteristics of 1FGL J1227.9–4852 allow for the possibility that it could be a rotation-powered pulsar. In order to investigate this, we searched the source for pulsed radio signals at the Parkes telescope in Australia, first on 2009 November 25.

We used the central beam of the Parkes multibeam receiver centred at a frequency of 1390 MHz to record data for a total of 2.0 h. The telescope was pointed at RA = $12^{\text{h}}27^{\text{m}}50.4^{\text{s}}$, Dec. = $-48^{\circ}51'54''$, with a beam FWHM = 14 arcmin; the beam size is sufficient that the LAT source error ellipse is entirely covered at >90 per cent of the nominal sensitivity. Total radio power was sampled every 125 μs from each of 512 channels spanning a bandwidth of 256 MHz (more details of the observing setup are given in e.g. Manchester et al. 2001).

The data were analysed using standard pulsar search techniques implemented in PRESTO (Ransom 2001). We searched a dispersion measure (DM) range of 0–270 pc cm $^{-3}$, which comfortably includes the maximum possible electron column density in this direction according to the Cordes & Lazio (2002) model. To allow for the possibility of a MSP in a tight binary, where the observed pulsar period P varies due to Doppler shifts, the search accounted for a large range of possible accelerations (assumed constant, up to ZMAX = 200 in PRESTO). No significant pulsar candidates were identified.

The nominal sensitivity limit of our search, assuming a pulse width of $0.1 P$, is approximately 0.06 mJy for a long-period pulsar. This limit degrades rapidly for short (millisecond) periods, especially for high values of DM/ P . Nevertheless, this search would have detected most millisecond (or young) pulsars known in the disc of the Galaxy. A potential caveat is that the received flux from a nearby pulsar may vary greatly due to interstellar scintillation; binaries may also experience eclipses. We therefore repeated this observation twice, for 1.1 h on 2010 July 18 and 1.0 h on 2010 November 12. We analysed the data in a similar manner, but again detected no pulsar signals. There is therefore no evidence that 1FGL J1227.9–4852 harbours a radio pulsar beamed towards the Earth.

2.4 ESO VLT and archival optical and IR observations

A search of public archival observations finds no deep observations at ultraviolet, optical or infrared wavelengths; there are no *Spitzer* observations of this field. XSS J12270–4859 has a 2MASS and DENIS counterpart with magnitudes ranging from 15.78 in the I band to 15.3 in the K_s band; it should be noted that this source has been observed to flicker in the optical with variations of >1 mag on time-scales of <15 min (Pretorius 2009). There is no counterpart to the new radio source (J122806–485218) in the 2MASS (Skrutskie et al. 2006) or DENIS catalogues at the position of the core up to $K_s > 14.3$, $H > 15.1$, $J > 15.8$ and $I > 18.5$ mag.

To identify the potential host galaxy of the new radio source J122806–485218 we performed imaging and spectroscopic observations of the field around RA = $12^{\text{h}}28^{\text{m}}05^{\text{s}}.01$, Dec. = $-48^{\circ}52'21''.3$ (J2000) with the ESO Very Large Telescope FOCAL Reducer and low-dispersion Spectrograph (VLT FORS2). Pre-imaging data in the R_SPECIAL filter were collected on 2010 February 10; to detect candidate host galaxies we executed a set of four 15-s exposures.

Photometric observations were reduced for bias and flat-field using calibration frames available for the night of observations.

Magnitudes of isolated galaxies were measured using SExtractor (Bertin & Arnouts 1996). One of the galaxies in the field is blended with a neighbouring star; to measure its magnitude we have fitted a PSF profile to the star and subtracted it from the image. The magnitudes of the galaxies were then measured using the elliptical aperture in SExtractor. From the galaxies in the field, two are the most probable candidates for the host galaxy:

(i) Galaxy1 at RA = $12^{\text{h}}28^{\text{m}}06^{\text{s}}.05$, Dec. = $-48^{\circ}52'16''.32$ (J2000) with $R = 18.17 \pm 0.04$ mag is located less than 2 arcsec from the brighter eastern component of J122806–485218.

(ii) Galaxy2 at RA = $12^{\text{h}}28^{\text{m}}05^{\text{s}}.42$, Dec. = $-48^{\circ}52'18''.79$ (J2000) with $R = 20.19 \pm 0.12$ mag lies between the eastern and western components.

In order to obtain the redshifts of the candidates, the following spectroscopic observations were conducted using the ESO VLT FORS2 in MXU mode and a mask with slits for nine objects. We chose grism (300I) which samples a wide wavelength range from 5000 Å to 11 000 Å. A set of four 1200-s exposures was performed on 2010 July 15. Collected spectroscopic data were reduced twice using different tools; the ESO FORS pipeline and the NOAO IRAF package. Poor conditions and inadequate sky subtraction precluded sensitive measurements of the two most probable host galaxies, mentioned above; it was not possible to extract 1D spectra with signal-to-noise ratios sufficient to identify any emission or absorption lines and to measure redshift.

3 DISCUSSION

By assuming that 1FGL J1227.9–4852 is associated with either the LMXB XSS J12270–4859 or the new radio source J122806–485218, we can combine the data from observations discussed in Section 2 to construct the broad-band spectral energy distribution shown in Fig. 8. We calculated a 2σ X-ray upper limit for J122806–485218 from the data set analysed by de Martino et al. (2010) by using the standard *XMM-Newton* PPS sensitivity map and assuming a simple power law with a photon index of 2. This gave a flux upper limit of $\sim 2 \times 10^{-14}$ erg cm $^{-2}$ s $^{-1}$.

The observed characteristics of 1FGL J1227.9–4852 do not allow a definitive source classification. There is no clear indication of variability in the γ -ray band to be correlated with other wavelengths; and there is no significant periodic signal that could be attributed to a spin or orbit. 1FGL J1227.9–4852 is a persistent, stable emitter with an exponentially cut-off power-law spectrum that lies approximately 14° off the Galactic plane. Within the LAT source error circle is a single bright, persistent X-ray source, the LMXB XSS J12270–4859, and a relatively bright, newly detected, persistent radio source J122806–485218. The possibility exists that 1FGL J1227.9–4852 is related to neither of these multiwavelength counterparts in which case little more can be said about its nature.

To place this unidentified γ -ray source in context we must note that active galactic nuclei (AGN) constitute the largest group of identified *Fermi* sources (~ 80 per cent) (Abdo et al. 2010a,c) and the vast majority of these are seen as blazars. Conversely, the Galactic source population is in the minority. It is principally composed of rotation-powered pulsars with small numbers of HMXBs, supernova remnants, globular clusters and pulsar wind nebulae. The pulsars all exhibit exponentially cut-off power-law spectra and are identified through the detection of pulsations in γ -rays.

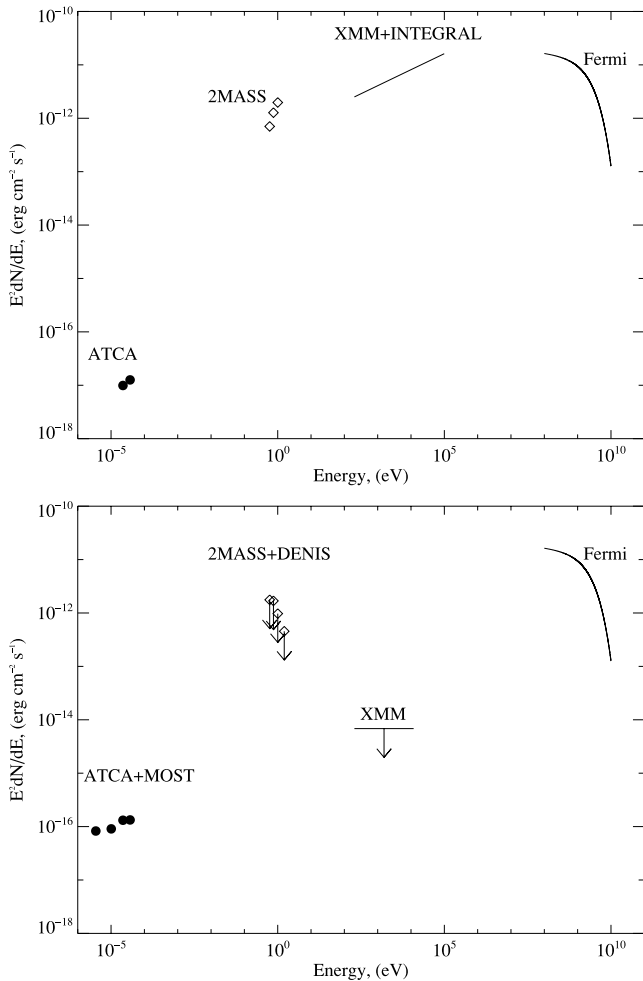


Figure 8. *Fermi*-LAT SED of 1FGL J1227.9–4852 overlaid on the overall SED of: (a) the LMXB XSS J12270–4859 (top panel) and (b) the new compact double radio source discovered by ATCA, J122806–485218 (bottom panel). Radio, optical, X-ray and γ -ray bands are plotted.

3.1 Is the γ -ray source Galactic in nature?

3.1.1 An isolated pulsar?

The γ -ray characteristics of 1FGL J1227.9–4852 are highly reminiscent of the population of γ -ray pulsars which have been identified in the first few years of observations of *Fermi*-LAT (Ray & Saz Parkinson 2011). While the photon index $\Gamma = 2.20$ and cut-off energy of 4 GeV are rather steep and high, respectively, compared to the typical LAT detected pulsars (Ray & Saz Parkinson 2011), there are two LAT detected γ -ray pulsars with photon indices >2.2 (PSR J0659+1414 and PSR J1833–1034, see Abdo et al. 2010b). Additionally there are LAT-discovered MSPs that share similar characteristics; PSR J0218+4232 and PSR J0437–4715 have photon indices of 2.0 and 2.1 and cut-off energies of 7 and 2.1 GeV, respectively (Abdo et al. 2009e). The location of 1FGL J1227.9–4852 off the Galactic plane would suggest that if it is a pulsar then it would likely belong to the population of MSPs. However, searches for pulsations both in γ -rays with the LAT and in radio with Parkes have not yielded any significant detection (see Section 2.1.1). The Parkes searches were sensitive to almost any known radio MSPs beamed towards the Earth, and there is therefore no direct evidence that 1FGL J1227.9–4852 contains such a pulsar. The low flux of

0.18 mJy at 5.5 GHz of XSS J12270–4859 is consistent with what would be expected from an isolated pulsar. The spectral index is 0.5 ± 0.6 , which is not as steep as would be expected from a pulsar (see e.g. Kramer et al. 1999; Kijak et al. 1998). While this does not rule out an isolated pulsar nature of the source, it does decrease its probability.

3.1.2 A pulsar in a binary?

Binary evolution theory explains the origins of MSPs as ‘recycled pulsars’, pulsars that once had a much longer spin period and had a low-mass binary companion. The pulsar accretes matter through Roche lobe overflow and is seen as a bright X-ray source, an LMXB. Through the accretion process angular momentum is transferred to the pulsar, effectively spinning it up to millisecond periods. Once the accretion rate drops low enough magnetic pressure can be sufficient to prevent further matter being accreted, at which point the rotation-powered radio pulsations can be seen.

Targeted radio follow-ups of >100 of the unidentified 1FGL sources have discovered 18 new MSPs in addition to the 11 radio MSPs detected by the LAT (Ray & Saz Parkinson 2011). If the γ -ray source was associated with a pulsar in a binary, possibly the LMXB XSS J12270–4859, then the modulation of the binary orbit would make searching for pulsations much more difficult due to the combination of the orbital motion and potential eclipses.

Interpreting XSS J12270–4859 as a millisecond binary pulsar explains the observed short orbital period, low X-ray luminosity with eclipses and flares, optical modulation from the irradiated companion and the presence of radio emission (see e.g. Bogdanov, Grindlay & van den Berg 2005, for PSR J0024–7204W in 47 Tuc). Since GeV emission has been detected from millisecond binary pulsars then this interpretation for XSS J12270–4859 also provides a coherent picture of the multi-wavelength observations and could associate it with the GeV source 1FGL J1227.9–4852. It should be noted that of the binary pulsars that are LAT sources, none shows GeV modulation at their orbital periods. This hypothesis presents two puzzles:

(i) The radio spectrum is not as steep as would be expected but this could be a result of free-free absorption making the spectrum flatter.

(ii) The optical spectroscopy shows emission lines (Masetti et al. 2006; Pretorius 2009) which are typical of accretion. However, all the optical spectroscopic measurements pre-date the launch of *Fermi* and since then the system may have transitioned from the accreting LMXB state to the rotation-powered pulsar phase.

PSR J1023+0038 is a system in which Archibald et al. (2009) suggest this has recently happened. Archibald et al. (2009) and Wang et al. (2009) discovered millisecond radio pulsations in the system; however, historical optical observations were very different from contemporary observations. The historic optical observations were very blue and exhibited rapid flickering of ~ 1 mag indicative of an accretion flow; this behaviour is similar to what has been seen in XSS J12270–4859 (de Martino et al. 2010). Recently Tam et al. (2010) reported the detection of HE γ -ray emission at the 7σ level at a position consistent with PSR J1023+0038; no pulsations were detected in the γ -ray data but a steep γ -ray spectrum with a power-law photon index of ~ 2.9 was observed. Investigating the γ -ray to X-ray luminosity ratio in PSR J1023+0038 and XSS J12270–4859 we find that both sources are a factor ~ 10 brighter in γ -rays.

Could XSS J12270–4859 be a system similar to PSR J1023+0038? If 1FGL J1227.9–4852 is indeed a MSP with a

short orbital period, this could explain why pulsations have yet to be detected from the source. The absence of any recent optical spectroscopy of XSS J12270–4859 means that we do not know if it is still an accreting source in the *Fermi* era. If new optical spectra were to show no signatures of accretion then the case for XSS J12270–4859 being a millisecond binary pulsar would be significantly strengthened. The hard X-rays detected by *INTEGRAL* would be unexpected in the case of a non-accreting MSP. However XSS J12270–4859 is reported as a weak persistent source in the latest catalogue (Bird et al. 2010) with a detection level of 10.2σ in ~ 1 Ms of exposure and it should be noted that all of the data used precede the launch of *Fermi* and could have been while the source was acting as an accreting LMXB. An interesting historical note is that when PSR J1023+0038 was initially discovered it was believed to be the first radio selected cataclysmic variable (Thorstensen & Armstrong 2005; Bond et al. 2002) in much the same way that XSS J12270–4859 was initially classified as a cataclysmic variable.

3.2 Is the γ -ray source extragalactic in nature?

The largest population of associated high-latitude ($b > 10^\circ$) LAT sources are AGN, all of which are radio sources at some level (Abdo et al. 2010a). Hence, despite J122806–485218 being at the edge of the LAT source 99.7 per cent error circle, as it is by far the brightest potential radio counterpart and has an AGN-like morphology it initially appears to be a strong candidate as the counterpart to 1FGL J1227.9–4852. The new radio source, J122806–485218, has a double morphology often seen in radio-loud AGN; it can be identified as either a core/jet structure (with the brightest component marking the position of the radio core and the weaker one being a hotspot in a jet), or as a roughly symmetric pair of radio lobes separated by ~ 10 arcsec. The core has a spectral index of $\alpha = -0.72$, while the lobe has a much steeper index of $\alpha = -1.09$. Hence if 1FGL J1227.9–4852 is associated with this object then it appears to be of an extragalactic nature.

The majority of the AGN detected by the LAT are blazars. These are AGN where the line of sight is aligned with the jet axis. They are radio bright, variable and with flat or inverted ($\alpha \geq -0.5$) spectra. Radio galaxies are observed at higher angles and are generally less luminous. Their radio spectra are also steeper ($\alpha \leq -0.5$). The absence of γ -ray variability and a steep radio spectrum would suggest that J122806–485218 does not belong to the blazar class.

The radio galaxy Centaurus A has also been seen as an extragalactic source of γ -ray emission. Abdo et al. (2010d) report the detection of HE γ -rays specifically from the giant radio lobes of Cen A and that the lobe flux contributed the majority of the emission. This was interpreted as inverse Compton scattered radiation from the cosmic microwave background (CMB), with additional contribution at higher energies from the infrared-to-optical extragalactic background light (EBL). Could the radio lobe in J122806–485218 also upscatter CMB photons to γ -ray energies creating the emission of 1FGL J1227.9–4852? The lack of γ -ray variability would be expected in such a case and this scenario can give a large γ to radio ratio at high redshift because lobe electrons upscatter CMB photons whose energy density increases as $(1+z)^4$. The ratio of the γ to radio luminosities is proportional to the ratio of energy densities in the magnetic (B) field and CMB and is shown below:

$$\begin{aligned} \frac{L_{\text{radio}}}{L_\gamma} &\propto \frac{U_B}{U_{\text{CMB}}} = \frac{B^2/8\pi}{4 \times 10^{-13} (1+z)^4} \\ &= 10^{-5} \\ \Rightarrow B &\sim 10^{-8} (1+z)^2 \text{ Gauss.} \end{aligned}$$

This is much lower than the μGauss magnetic fields typically invoked for extended radio structures in jetted AGN (e.g. Kataoka & Stawarz 2005). One explanation is that the synchrotron emission is vastly underestimated and would require there to be large scale diffuse emission. However, there is no evidence of large scale diffuse emission in the GMRT observations, effectively ruling out the up-scattering of CMB photons in the radio lobe of J122806–485218 as a viable explanation for the γ -ray emission of 1FGL J1227.9–4852. This conclusion is further supported by the particularly high γ -ray to X-ray ratio implied by the *XMM* upper limit as copious X-rays would be generated via the same processes as γ -rays within the lobes.

4 CONCLUSIONS

The unidentified *Fermi* source 1FGL J1227.9–4852 is an intriguing source that may potentially be associated with either the bright X-ray source XSS J12270–4859 or the new radio source J122806–485218, which have been identified within the LAT error circle. However, the specific nature of this object is still unclear and it may not be firmly associated with either of these two objects yet. The emission is unlikely to be from a blazar jet as no flat-spectrum radio source is identified. Investigating the possibility that the radio lobe of J122806–485218 can upscatter CMB photons to high energies implies that this is a very unlikely scenario based upon the observed radio and γ -ray luminosities. The source may be yet another example of the radio-faint/quiet γ -ray pulsars detected by *Fermi*, with the non-detection indicating that current γ -ray pulsation searches have not been sensitive enough. The blind searches carried out to date on the LAT data would not have detected either an MSP or a binary pulsar.

Based upon the available observations, we favour the hypothesis that 1FGL J1227.9–4852 is associated with XSS J12270–4859 as the least improbable association, in the scenario that the system has evolved from an accreting LMXB phase to a millisecond binary pulsar state. If this is the case it would be an exciting link in understanding binary evolution. New optical spectroscopic measurements of XSS J12270–4859 will indicate whether it is still an accreting source or whether it may have transitioned to be a new millisecond binary pulsar. Further searches for a new pulsar in the field will allow for a more confident assessment of the likelihood of pulsar origin of the γ -rays. Another key to identifying the nature of this source may be in correlated variability at multiple wavelengths. However, to date there has been no indication of any variability in the GeV band. Of course, the possibility remains that 1FGL J1227.9–4852 is something entirely different, as the source has not as yet been associated with a multiwavelength counterpart.

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REFERENCES

- Abdo A. A. et al., 2009a, *ApJ*, 699, 817
 Abdo A. A. et al., 2009b, *ApJ*, 701, L123
 Abdo A. A. et al., 2009c, *ApJ*, 706, L56
 Abdo A. A. et al., 2009d, *Sci*, 325, 840
 Abdo A. A. et al., 2009e, *Sci*, 325, 848
 Abdo A. A. et al., 2009f, *Sci*, 326, 1512
 Abdo A. A. et al., 2010a, *ApJ*, 715, 429
 Abdo A. A. et al., 2010b, *ApJS*, 187, 460
 Abdo A. A. et al., 2010c, *ApJS*, 188, 405
 Abdo A. A. et al., 2010d, *Sci*, 328, 725
 Archibald A. M. et al., 2009, *Sci*, 324, 1411
 Atwood W. B. et al., 2009, *ApJ*, 697, 1071
 Bertin E., Arnouts S., 1996, *A&AS*, 117, 393
 Bird A. J. et al., 2010, *ApJS*, 186, 1
 Bogdanov S., Grindlay J. E., van den Berg M., 2005, *ApJ*, 630, 1029
 Bond H. E., White R. L., Becker R. H., O'Brien M. S., 2002, *PASP*, 114, 1359
 Butters O. W., Norton A. J., Hakala P., Mukai K., Barlow E. J., 2008, *A&A*, 487, 271
 Cordes J. M., Lazio T. J. W., 2002, preprint (arXiv:astro-ph/0207156)
 Cusumano G. et al., 2010, *A&A*, 510, A48
 de Martino D. et al., 2010, *A&A*, 515, A25
 Kataoka J., Stawarz L., 2005, *ApJ*, 622, 797
 Kijak J., Kramer M., Wiełebinski R., Jessner A., 1998, *A&AS*, 127, 153
 Kramer M., Lange C., Lorimer D. R., Backer D. C., Xilouris K. M., Jessner A., Wiełebinski R., 1999, *ApJ*, 526, 957
 Lomb N. R., 1976, *Ap&SS*, 39, 447
 Manchester R. N. et al., 2001, *MNRAS*, 328, 17
 Masetti N. et al., 2006, *A&A*, 459, 21
 Mattox J. R. et al., 1996, *ApJ*, 461, 396
 Mauch T., Murphy T., Buttery H. J., Curran J., Hunstead R. W., Piestrzynski B., Robertson J. G., Sadler E. M., 2003, *MNRAS*, 342, 1117
 Pretorius M. L., 2009, *MNRAS*, 395, 386
 Ransom S., 2001, PhD thesis, Harvard University
 Ray P., Saz Parkinson P. M., 2011, in Rea N., Torres D. F., eds, *Proc. of ICREA Int. Workshop on the High-Energy Emission from Pulsars and their Systems*. Springer, Berlin, preprint (arXiv:1007.2183)
 Saitou K., Tsujimoto M., Ebisawa K., Ishida M., 2009, *PASJ*, 61, L13
 Sault R. J., Killeen N. E. B., 2010, *The Miriad User's Guide*, Australia Telescope National Facility, Sydney (<http://www.atnf.csiro.au/computing/software/miriad>)
 Sault R. J., Wieringa M. H., 1994, *A&AS*, 108, 585
 Sault R. J., Teuben P. J., Wright M. C. H., 1995, in Shaw R. A., Payne H. E., Hayes J. J. E., eds, *ASP Conf. Ser. Vol. 77, Astronomical Data Analysis Software and Systems IV*. Astron. Soc. Pac., San Francisco, p. 433
 Saz Parkinson P. M. et al., 2010, *ApJ*, 725, 571
 Scargle J. D., 1982, *ApJ*, 263, 835
 Skrutskie M. F. et al., 2006, *AJ*, 131, 1163
 Tam P. H. T. et al., 2010, *ApJ*, 724, L207
 Thorstensen J. R., Armstrong E., 2005, *AJ*, 130, 759
 Ubertini P., Sguera V., Stephen J. B., Bassani L., Bazzano A., Bird A. J., 2009, *ApJ*, 706, L7
 Wang Z., Archibald A. M., Thorstensen J. R., Kaspi V. M., Lorimer D. R., Stairs I., Ransom S. M., 2009, *ApJ*, 703, 2017

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